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FTTS Powered Trailer - "A Systems Approach"

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ABSTRACT

This paper summarizes the results of work accomplished jointly by SEI and TARDEC/NAC on the Powered Trailer Technology CRADA program (CRADA #04-02).

A systems approach for identifying FTTS powered trailer requirements and technologies is presented along with results of a Quality Function Deployment (QFD) analysis of the Maneuver Sustainment Vehicle (MSV) trailer requirements and applicable technology solutions. The QFD analysis was useful for prioritizing requirements and assessing technologies based on performance, cost and risk.

Tradeoff evaluations among trailer power drive concepts are presented. These include Electric Drive, Hybrid Electric Drive, Hybrid Hydraulic Drive, Mechanical Power Take Off, and Internal Combustion Engine (ICE) Drive. System Block Diagrams and performance summaries (mobility assist performance, weight, interoperability, design complexity, etc.) were generated to illustrate the advantages and disadvantages of each concept.

ProE CAD models have been used to illustrate potential design layouts, packaging issues, and interfaces. Results of the coupled transport/trailer vehicle mobility analysis are provided to highlight the benefits of trailer mobility assistance under real world operational conditions.

INTRODUCTION

Tactical trailers must support FTTS mission objectives. They must enhance mobility when coupled with the transport vehicle for grade climbing and operations in soft soil, and provide an enhanced aircraft (C-130) loading interface. Tactical trailers must also require minimal maintenance, and become part of the C4I network for cargo and health status reporting.

Figure 1 illustrates the systems approach used for identifying the preferred solution based on user requirements. It is the basic MIL-STD-499 System Engineering process supplemented by QFD analysis for requirements prioritization. Note that this process is iterative with feedback to the specification for requirement changes, and in some cases back to user requirements for changes in the deployment doctrine, tactics, or procedures.

The first step in the process was reviewing the FTTS Operational Requirements Document (ORD) and the FTTS MSV Performance Specification. A powered trailer Requirements Traceability/ Rationale Matrix (RTRM) was constructed based on this information. The 135 requirements are grouped into the major areas of Physical Characteristics, Cargo Handling and Management, Environmental Conditions, Battlefield Effectiveness, Transportability, Operational Performance, Tactical Mobility, Mission Profile, Interoperability, RAM, and Other Requirements.
All requirements are numbered with a brief description of the requirement and its source: ORD, SPEC, or DERIVED.

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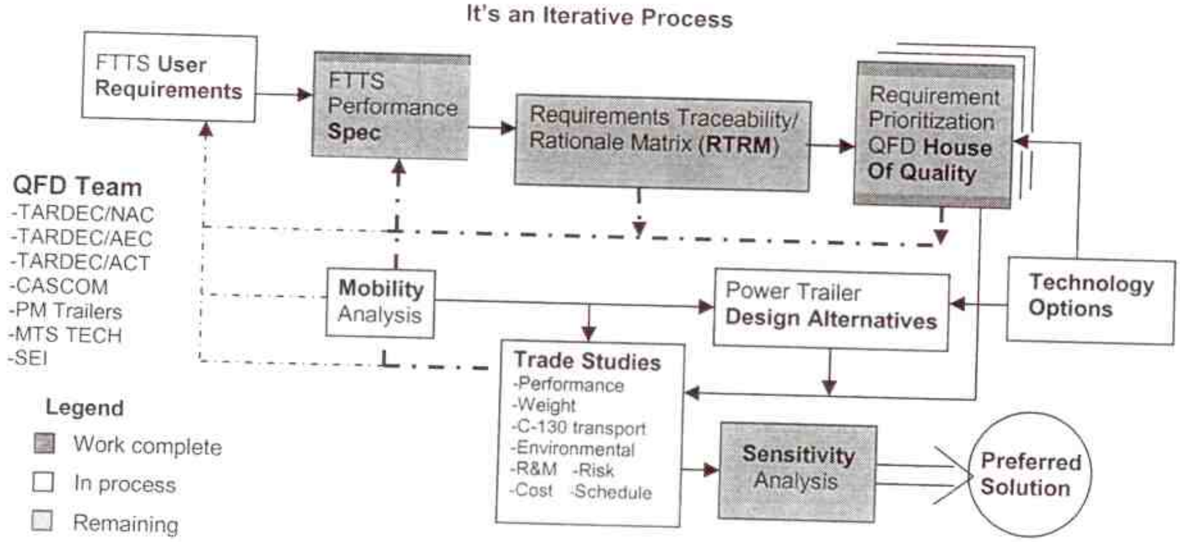
Figure 1 - Systems Approach



Requirement rationale and correlations are identified with desired timeframe for requirement implementation: Spiral 1 (ACTD), Spiral 2 (Prototype), or Spiral 3 (Production).

Quality Function Deployment

The next step involved using the QFD process/methodology to analyze customer requirements and tradeoffs. Trailer attributes (requirement descriptors) were examined against trailer technology options. The QFD "House of Quality" allowed customer requirements to be prioritized and interrelations between requirements and the technology options to be established. "House of Quality" is only the first phase of the QFD process. The process is followed throughout the development and production planning life cycle to subsequently establish design characteristics, part selections, and process/production planning activities.

Figure 2 provides a high-level view of inputs to the QFD. A detailed Powered Trailer "House of Quality" has been generated and is available upon request. The scope of this "House of Quality" was limited to MSV class trailer requirements versus Utility Vehicle (UV) class and the first spiral solution versus objective desires. Both positive and negative interrelationships were analyzed with results summarized in **Table 1**. Excel software was used to allow customer importance, % improvement, and interrelationship values to be adjusted and the relative importance of the technologies across the requirements to be readily assessed.

The QFD results indicate that the technologies providing the greatest benefits across the requirements are suspension, power stowage, propulsion, on-board diagnostics & prognostics, and communications with transport (C4I). The best approach for propulsion

(mobility assist) requires a tradeoff of trailer weight, packaging, and cost considerations against FTTS and interim commonality objectives. Results and tradeoffs are discussed herein.

Figure 2 – Powered Trailer "House of Quality"

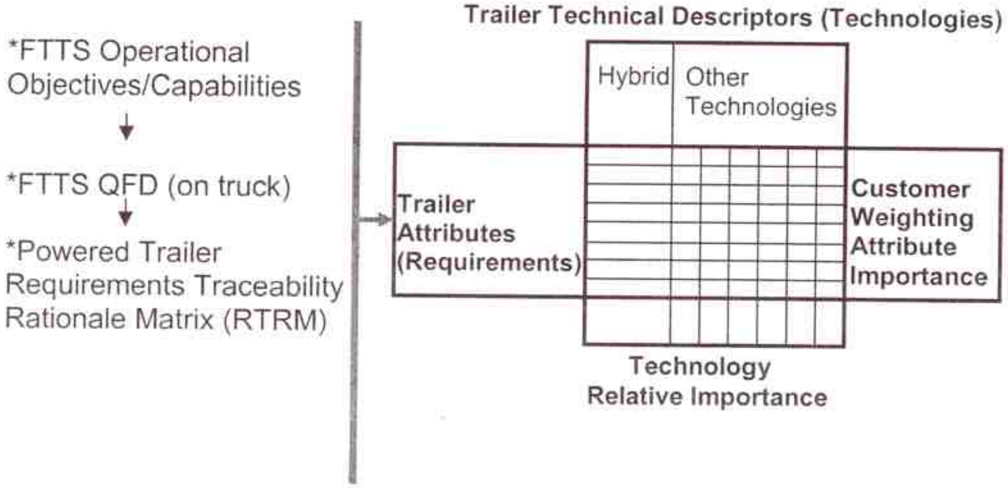


Table 1 - Summary of QFD Results

- Suspension characteristics very important; more so than number of axles, steering, and braking
- Power storage important for self-mobility, export power, and self-charging
- Internal Combustion Engine (ICE) only propulsion scores high for mobility assist but low for drive technology commonality
- On-board diagnostics & prognostics required

- Communications with transport important (C4I)
- For unmanned trailer survivability is less important; durability, however, remains important
- Smart tie down desired
- Modular Intermodal Platform (MIP) interface required, LHS and adjustable height deck are options
- Cargo tagging and configured load building software required but not trailer driven

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Horsepower/Torque Needs

FTTS mobility requirements were analyzed and estimates for trailer wheel drive horsepower and torque were calculated for mobility assist, dash capability of combined transport and trailer, and for trailer self-mobility.

FTTS Mobility Requirements:

- <20% degradation to prime mover
- 40% improved roads (paved and gravel), 60% unimproved (trails and cross-country)
- 7.5 to 18.1 mph over tactical terrain
- Ascend 2% grade at 55 mph
- Vertical step: 24", Trench crossing: 59"
- Fording: 48", 60" with kit
- Lane change at speeds up to 45 mph
- 6 watts average vertical absorbed power

Horsepower results are summarized in **Figure 3** assuming a minimum of 150 hp for wheel drive is available.

Figure 3 -Horsepower Summary

- **Mobility Assist**
  -150 hp is sufficient to not degrade transport mobility when negotiating a 30% grade at low speed (4 mph)
- **Dash Capability (0-30 mph in 12 sec)**
  -150 hp will not allow transport dash capability to be maintained without degradation, hp required increases significantly on non-level ground
- **Trailer Roll on/off C-130**
  -150 hp is sufficient to self-negotiate a 15 degree ramp (~27% grade) at speeds up to 5 mph (low speed torque is more critical)
  -150 hp is sufficient for self-mobility on asphalt and secondary roads (10% grade) at speeds up to 12 mph

In addition to horsepower, sufficient low speed torque output must be available from the power source to initiate and maintain trailer motion on cargo ramps. As a reference a 300 Vdc, 100 kW electric motor can generate 200 ft-lbs constant, 400 ft-lbs peak torque. Torque needed determines final drive gear ratios (reductions up to 30:1 are considered practical to achieve).

Table 2 provides an estimate of torque needed to climb aircraft ramps and for roll on/off ship assuming two-wheel drive and 75% drive train efficiencies.

Results indicate that the system alternatives evaluated can meet these requirements for short distances, assuming proper power source and gear reduction ratio selections.

Powered Trailer Design Concepts

The following powered trailer design concepts were postulated for meeting requirements:

ALT #1 Electric Power Take Off (PTO) -Electrical power take off obtained from the transport

ALT #2 Hybrid Electric Vehicle -Series hybrid electric vehicle with ICE, generator, and power pack

ALT #3 Hybrid Hydraulic Vehicle -Hydraulic boost with hydraulic power provided by the transport. A hydrostatic drive variant was also considered

ALT #4 Mechanical PTO -Mechanical power take off obtained from the transport vehicle

ALT #5 ICE Drive -ICE drive with a conventional drive train.

All the above concepts have a cargo capacity of 11 ST, and are restricted to 4 m high with flatrack/ISO container, and a width of 96 inches for road transport.

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Table 2 -Torque Summary

	C-130	C-5A- A/C LEVEL	C-5A- AFT KNEELED	C-17	RO-RO SHIP
Ramp slope, degrees	13.25	13.5	7.9	9 ramp, 15 ramp toe	15
Torque, ft-lbs	13,784*	19,422	11,770	17,576	21,593
Gear reduction	17:1	24:1	15:1	22:1	27:1

*13ST weight restriction

Features common to all alternatives include:

- 395/85 R20 XZL tires
- 2 axles
- Central Tire Inflation System (CTIS)
- Pneumatic Anti-lock Brake System (ABS)
- Serial communications with transport
  - -Control of mobility assist and CTIS
  - -Trailer health and load status data
- Trailer bed basic design
- Independent suspensions

Physical characteristics and system weights are summarized in **Table 3** and **Table 4**

Table 3 -Physical Characteristics

Dimensions (inches)	ALT#1 Electric	ALT#2 HEV	ALT#3 HHV	ALT#4 Mech PTO	ALT#5 ICE drive
Wheel Drive	4 x 2	4 x 4	4 x 2	4 x 2	4 x 4
Suspension	Double A-Arm	Double A-Arm	Trailing Arm	Either Type	Either Type
Length	280	328	285	280	328
Width	96	96	96	96	96
Deck Height	51.5	51.5	51.5	51.5	51.5
Ground Clearance	18	18	18	18	18
Track	81	81	79	81	81
Wheel Base	192	192	201	192	192

Table 4 -Power Trailer Weights

Weight (lbs)	ALT#1 Electric	ALT#2 HEV	ALT#3 HHV	ALT#4 Mech PTO	ALT#5 ICE drive
Basic Bed	5,745	5,745	5,745	5,745	5,745
Suspension & Power Drive	6,625	9,800	5,155	4,875	7,570
MIP	3,500	3,500	3,500	3,500	3,500
Cargo Capacity	22,000	22,000	22,000	22,000	22,000
Total	37,870 18.9 ST	40,695 20.3 ST	36,400 18.2 ST	36,120 18 ST	38,815 19.4 ST

Description of Drive Alternatives

ALT #1 Electric PTO
-Rear wheel motor drive. Two 300 Vdc 100 kW peak liquid cooled motors/inverters. 150 hp, electric steering, conventional steering when towed. Battery pack (36 kW-hr) with DC-AC power inverter for export power.

ALT #2 Hybrid Electric Vehicle
-Series HEV. Same drive as ALT#1, except 4-WD, with addition of a 100 - 120 hp diesel ICE and generator.

ALT #3 Hybrid Hydraulic Vehicle
-Hydraulic boost (800 ft-lb torque) with PTO provided by transport. Rear axle drive, 150 hp to drive axle.

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Assumes a hydraulic system operating pressure of 6000 psi. Recharge provided by combination of transport source and trailer regenerative braking. Hydraulic steering with conventional steering when towed.

Another variation, which offers greater performance, is a hydrostatic drive using (4) hydraulic drive motors. This provides 4-WD capability and reduces required torque and gear ratios per wheel. An ICE and pump provide system pressure.

ALT #4 Mechanical PTO

The axles are driven by the transport. Trailer is towed only, with articulating driveline/steering. The hp and torque available to the trailer axles is dependent on the transport's hp and torque output and the distribution desired over all axle lines. Assuming 200 hp and 725 ft-lb torque is available at the transport's rear axle and the trailer receives 50% of this, 100 hp and 363 ft-lb of torque will be available for trailer drive.

ALT #5 ICE Drive

4-WD with conventional drive train. 150 hp is available to drive axles. Assumes a 210 hp, 340 ft-lb torque diesel engine. Electrical steering actuator. Generator with inverter provides electrical export power.

System block diagrams were developed for each alternate to assist in understanding functions and interfaces. ProE models were then developed to help understand the physical constraints. **Figure 4** and **Figure 5** are representative of such data for ALT #1. **Figure 6** is ALT #5.

Figure 4 -ALT #1 Electric PTO Block Diagram

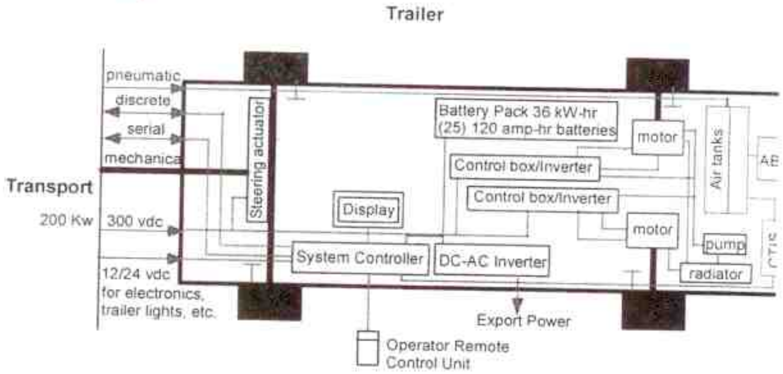
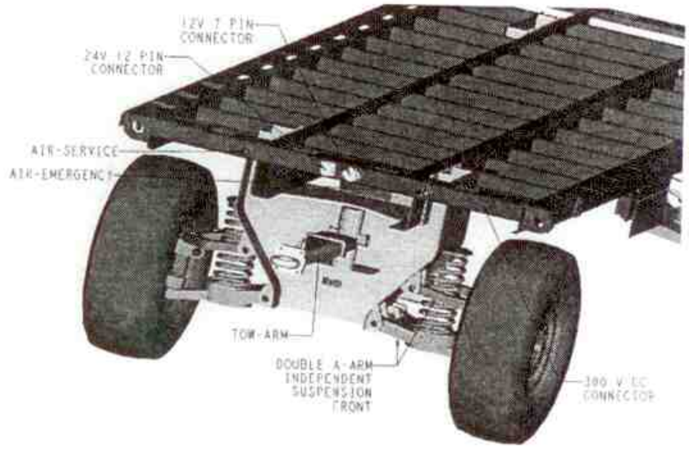


Figure 5 -ALT #1 Double A-Arm Suspension



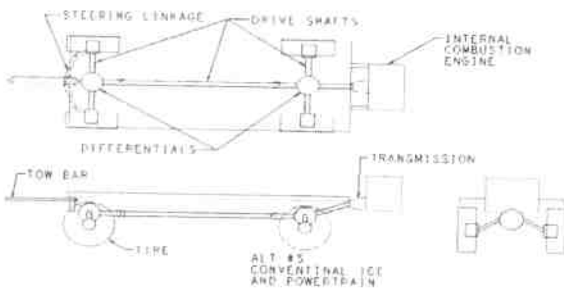


Figure 6 -ALT #5 ICE Drive

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Key Tradeoff Areas

A number of design tradeoffs surfaced during this study involving trailer mobility performance, weight, cost, packaging, and C-130 loading interface. Tradeoff studies are on-going in these areas.

-Mobility performance

Results of NRMM simulation and analysis on ALT #? and ALT #? are provided in **Table 5** based on trailer characteristics and suspension types. Maximum speed and percentage No-Go data indicates?

-Number of axles

A 2-axle configuration is preferred over 3 axles for reduced trailer weight and cost. One disadvantage is sensitivity to C-130 cargo load and CG location to ensure axle load on tread ways does not exceed C-130 loading limitations.

-4-WD Versus 2-WD

On-going mobility analysis will justify benefit versus additional cost/weight.

-Steering

Ackerman, skid steer, steer-by-wire, or other.

-Tire size

Larger diameter tires allow for increased ground clearance and potentially greater suspension travel. However, they increase the height of the trailer bed making it more difficult to lower the deck to 39 inches for C-130 ramp interface. As a compromise to better facilitate C-130 loading, 395/85 R20 (46.7" dia.) tires have been selected versus 16R20 (52.9" dia.).

-Packaging of drive components

Packaging of required drives, power storage and electronics is a challenge. Packaging design must not interfere with the ability of the trailer to carry and load/off-load cargo. Ground clearance must be taken into account to avoid mobility No-Go due to obstacle interferences with the bottom of the trailer. One concept is to mount the ICE on a platform which can be lowered to facilitate cargo transfer. Volume available for engine/generator is approximately 60 cu ft. Note that trailer departure angle must be ≥ 39 degrees.

-Trailer Frame/Bed Materials

Service life, strength, weight, and cost.

-Power storage technology

Performance, weight, and cost of current battery technologies versus super capacitors.

-Drive control strategy

Synchronization and control of the transport and trailer power drives.

-C-130 loading

Various ways to lower deck height for C-130 interface were explored. A squattable trailer deck may not be feasible due to design complexity, impacts on suspension, and added cost. Use of CTIS to help lower deck height helps but is not feasible due to increased drive torque requirements. **Figure 12** illustrates a concept for an adjustable mid-section deck with a side extension to facilitate the transfer of cargo pallets.

Table 5 - Mobility Results (In Process)

Concept	% NG	MRS ( )	MRS ( )
ALT #			
ALT #			

One approach for off-loading palletized cargo into the aircraft, without requiring K loaders, is to use two such trailers. **Figure 8** illustrates this concept.

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Advantages/disadvantages of each concept are summarized in **Table 6**: **ALT#1** provides required mobility assist with limited self-mobility. **ALT#2** performs well but has the highest weight and cost. **ALT#3** offers mature technology but extended self-mobility is not feasible without an ICE. Packaging of accumulators is also an issue. **ALT#4** offers the lowest weight and cost with simplified drive control but couples the trailer to the transport as a unit; self-mobility is lost and backward compatibility degraded. **ALT#5** appears to be a good compromise solution considering performance, weight, cost and interoperability. However, commonality with transport drive technology is lost and trailer drive control is more challenging.

Figure 7 - Side Extension Deployed

Figure 8 -Transfer of Pallets

Table 6 – Comparative Summary of Tradeoff Results

G=Better Y=OK R=Worst	Mobility Assist	Self Mobility	Weight	Complexity (RAM)	Inter-opera bility	Maturity	Procure-ment Cost	Common-ality
ALT#1 Elect PTO	G	Y	Y	Y	Y	Y	Y	G
ALT#2 HEV	G	G	R	R	G	Y	R	G
ALT#3 HHV	G	R	G	Y	Y	G	Y	Y
ALT#4 Mech PTO	Y	R	G	G	R	G	G	R

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ALT#5 ICE Drive	G	G	Y	Y	G	G	G	R

Conclusions

The comparison of design alternatives is consistent with QFD findings. However, sensitivity analysis remains to be done. The best powered trailer design approach is dependent on final trailer operational requirements and the next level of QFD (Parts Deployment). There are also other factors to consider, such as commonality of design with that of the transport, which simplifies drive control and offers Life Cycle Cost benefits.

Although there is commonality between the FTTS transport and companion trailer requirements, there are differences in drive duty cycles, self-mobility performance, export power needs, and survivability criticality. There are also differences in their respective cost targets.

Further iterations of the "Systems Approach" presented herein will be required to determine which technology options provide the greatest benefits. The planned strategy of conducting Technology Rodeos will assist in this process.

Improved grade climbing and mobility in soft soil along with cargo/health status reporting (C4I networking), lower maintenance, and easier cargo loading will emerge as the key benefits of a powered trailer.

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Additional Sources

Documentation and data referenced in this article can be obtained through the FTTS ACE. Access to the ACE can be obtained from Nance Halle.